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Regular paper

Determination of axial flux motor electric parameters by the analytic-finite elements method

This paper describes the electric parameters determination for an axial flux permanent magnets synchronous motor, using the joined method analytic/finite elements. Indeed several models of mutual and principal inductances and electric motor constant are developed analytically and validated by the finite elements method. These models are fortunately parameterised allowing to the formulation of several optimisation problems such us the motor ripple torque.

KEYWORDS: Finite elements, analytic method, Mutual inductance, electric motor constant, torque, electromotive force.

1. INTRODUCTION

Brushless permanent magnet motor operation consists in the conversion of energy from electrical to magnetic to mechanical. Because magnetic energy plays a central role in the production of torque, it is necessary to formulate methods for computing it.

In deed there are numerous ways to determine the magnetic field distribution within an apparatus. For very simple geometries, the magnetic field distribution can be found analytically. However, in most cases, the field distribution can only be approximated.

Magnetic field approximations appear in two general forms. In the first, the direction of the magnetic field is assumed to be known everywhere within the apparatus. This leads to magnetic circuit analysis, which is analogous to electric circuit analysis. In the other form, the apparatus is discretized geometrically, and the magnetic field is numerically computed at discrete points in the apparatus. This approach is commonly called finite element analysis.

Permanent magnets Synchronous motors with axial flux (PMSMAF) were the subject of several research tasks which increasing in the last few years [1]. This increase is due to the advantages which the PMSMAF presents in structure, reduced volume, and as performance and the significant torque at low speed. The determination of the parameters of the PMSMAF is a precondition necessary for any applications of the electric motion [7].

In this paper, a model of the electric motor parameters is established in order to fix on the one hand variables influencing certain performances such as : ripple torque and motor converter consumption and on the other hand to use it in the variable speed control approaches.

2. MOTOR STRUCTURE

The axial flux permanent magnets motor employed in this study is made with four poles pairs and six main teeth, between which six teeth are inserted in order to improve the electromotive wave-form and to reduce leakage flux [2]. Figure 1 illustrates a frontal view of the studied configuration.

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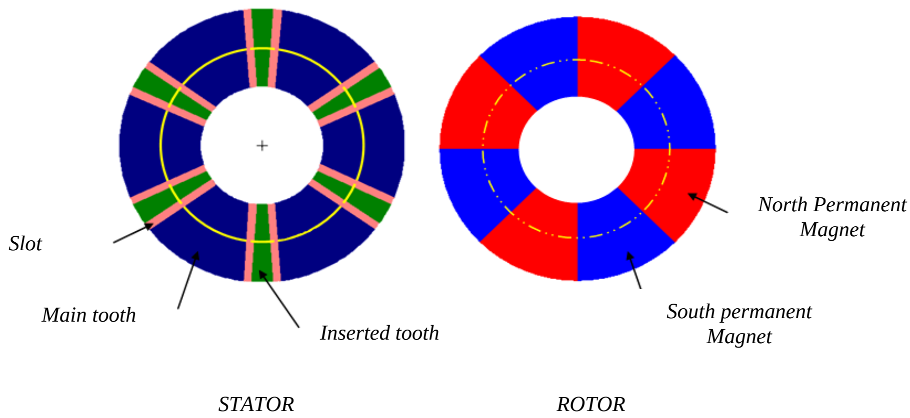


Figure 1: Front view of the four poles pairs and six main teeth of the motor

Each winding is composed by two diametrically opposite coils surrounding the main teeth. There are two configurations witch depends from back electromotive force (back E.M.F.) wave form witch can be sinusoidal or trapezoidal.

3. MOTOR MODELING

Motor dimensions and electric parameters are calculated by analytical method [3]. To validate this dimensioning method, the motor is drawn according to its geometrical magnitudes extracted from the analytical model with the software MAXWELL-2D [10].

3.1. Analytical model of the motor

We treated in this paper the analytical model of the motor with the trapezoidal wave form and the sinusoidal wave form

- ✓ Trapezoidal wave form structure

The magnetic induction is supposed with a rectangular wave form into the air gap (figure 2).

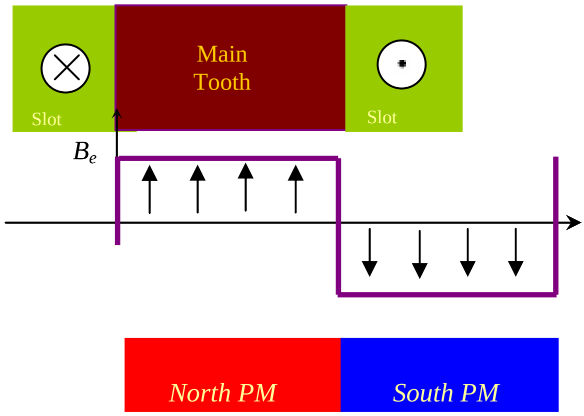


Figure 2: Air gap induction in trapezoidal configuration

The electromotive force per phase value is proportional to the angular speed, the number of spire per phase and the flux variation, is given by the following expression:

$$E = -N_{sph}\,\frac{d\Phi}{d\theta}\cdot\frac{d\theta}{dt} \tag{1}$$

$$E = N_{sph}\cdot\left(\frac{D_{ext}^2 - D_{int}^2}{4}\right).B_e\,.\Omega \tag{2}$$

$$\theta = \frac{d\Omega}{dt} \tag{3}$$

where:

B_e : induction in the air-gap,

N_{sph} : number of spires per phase,

D_{int} : internal diameter,

D_{ext} : external diameter,

Φ : flux value,

θ : angular speed.

The electric constant is given by:

$$K_{e_{trap}} = \frac{N_{sph}}{2}\cdot(D_{ext}^2 - D_{int}^2)\cdot B_e \tag{4}$$

For trapezoidal supply currents in phase with the back E.M.F, the instantaneous power is equal to its average value [7]:

$$P_{e_{trap}} = 2.E.I \tag{5}$$

Where E and I are respectively the maximum value of the back electromotive force and the maximum current value.

The torque is given by:

$$C_{m_{trap}} = K_e.I \tag{ 6}$$

So,

$$C_{m_{trap}} = N_{sph}\cdot\left(\frac{D_{ext}^2 - D_{int}^2}{2}\right).B_e.I \tag{7}$$

- ✓ Sinusoidal wave form structure

The magnetic induction is showed in the figure 3.

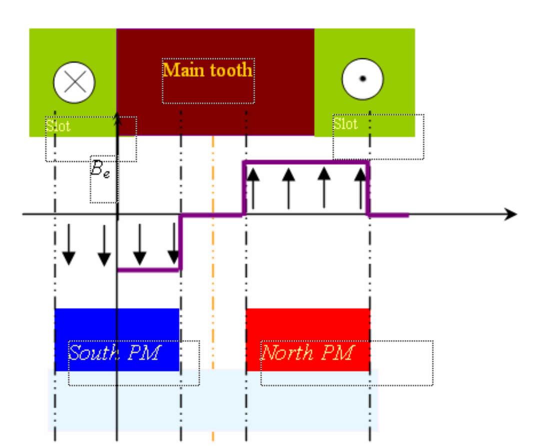


Figure 3: Air gap induction in sinusoidal configuration

When the motor is supplied with sinusoidal currents in phase with the back electromotive forces, the torque takes the following form:

$$C_{em_{sin}} = \frac{3}{2} K_{e_{sin}} I \tag{8}$$

where $K_{e_{sin}}$ is the electric constant of the back E.M.F.

The maximum value of back E.M.F. at maximum speed is given by the following expression:

$$E_{phi} = \frac{3}{2} K_e \Omega_{max} \tag{9}$$

The electric constant is given by:

$$K_{e_{sin}} = \frac{3}{2} . N_{sph} . (\frac{D_{ext}^2 - D_{int}^2}{4}) . B_e \tag{10}$$

3.2. Analytical model of inductance

In this type of motor, the value of the inductance is low because the flux created by the coil crosses the air gap and the magnet thickness.

For the inductance calculation, the motor is supplied by its peak current, and the magnets are replaced by air [8], then we obtain the flux lines distribution witch illustrated by the figure 4.

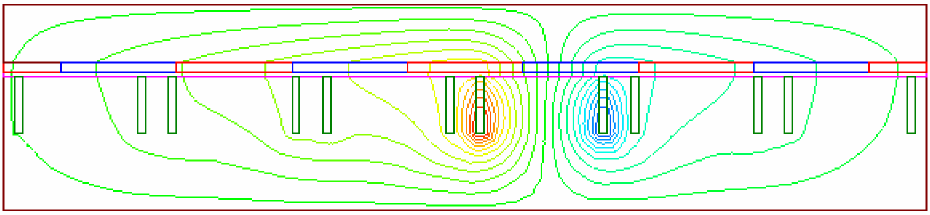


Figure 4: Flux lines distribution around one stator pole

For a linear system, the inductance value of the phase constituted by two coils may be obtained from [5]:

The energy calculation

$$L = \frac{2}{I^2}.A.\iint_{area} B_m H.ds \tag{11}$$

The flux calculation

$$L = \frac{N_{sph}}{I}.\frac{1}{A_{slot}}.A.\int A.ds \tag{12}$$

Where B_m is the flux density, H is the magnetic field, A_{slot} is the slot area, and A is a scalar potential.

The phase of the all configurations is expressed as follows:

$$L = \frac{3\mu_0}{N_{te}}.\left(\frac{S_{enc}}{e+t_m} + \frac{A.H_d}{2.L_{enc}}\right).N_{sph}^2 \tag{13}$$

Where, S_{slot} is the slot area, H_d is the slot height, L_{enc} is the slot width, e is the air gap thickness and N_{te} is the teeth number.

3.3. Analytical model of resistance

The phase resistance is given by the following formulations respectively for trapezoidal and sinusoidal configurations [6]:

$$R_{ph\_trap} = \rho(T_b).N_{sph}.l_{sp}.\frac{2}{I_c}.\delta \tag{14}$$

$$R_{ph\_sin} = \rho(T_b).N_{sph}.l_{sp\_sin}.\frac{2}{I_{eff}}.\delta \tag{15}$$

Where l_{sp_trap} and l_{sp_sin} are respectively the average whorl lengths for the trapezoid and sinusoidal configurations, I_c is the trapezoidal peak current value and I_{eff} is the sinusoidal effective current value. ρ is the copper resistivity at the winding temperature T_b, it is expressed by the following function:

$$\rho(T_b) = rcu[1 + \alpha(T_b - 20)] \tag{16}$$

4. SIMULATIONS

The knowledge of electromagnetic fields when designing electric motor is primordial, considering the physical complexity of the phenomena which proceed there. This knowledge contributes to determine the losses and the forces for the realization of the electro-technical devices [6]. In this context, it is significant to have a model which represents correctly the reality and to calculate necessary flux used for the calculation of the electric parameters of the motors. With this intention, the only methods available are those which use the finished differences or the finite elements.

In this paper, we used the finite element method used by several computation fields softwares such as FLOW 2D developed in the E.N.S.I.E.G. of Grenoble, OPERA distributed by Vector Field and Quick Field de Tera Analysis and MAXWELL 2-D distributed by Ansoft Corporation in the United States and which is used in our study [7]. MAXWELL 2D software [5], is a dedicated for the motors electromagnetic fields analysis having complex structure. It uses the finite element method to solve the electromagnetic problems all while being based on a two-dimensional geometrical representation [4]. The software architecture can be schematized as the following figure 5.

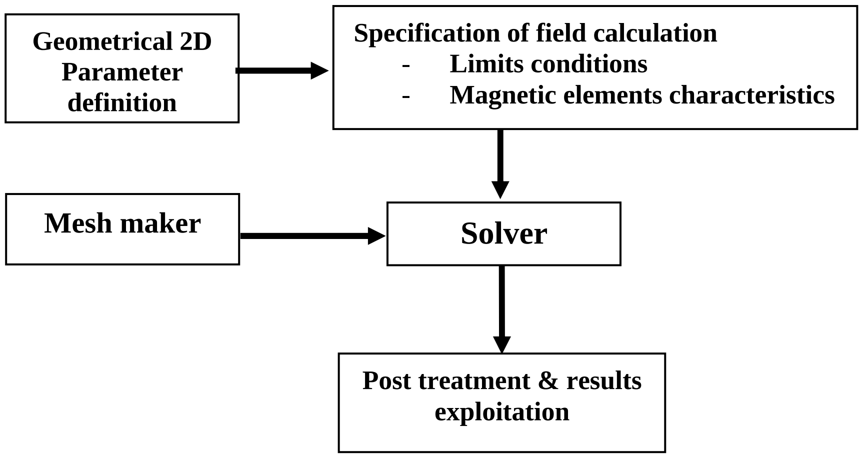


Figure 5: Software architecture of calculation by finite elements

4.1.Motor parameters determination

The electric motor parameters are carried out by the magnetic flux calculation developed by the motor. On the basis of a two-dimensional geometrical representation of cylindrical cross section on the average diameter of the motor (figure 6), stator windings are supplied with current in order to calculate magnetic flux values.

<u>Cylindrical cut plan transformation</u>

The engine can be studied in 2D by decomposition in cylindrical plans of cuts in order to reduce the time of simulation. The variation of surface between magnet and a principal tooth is not linear because of the principal edges. So that, in order to find the true variation of flux, it is necessary to study the motor on several plans of cylindrical cuts.

In order to use the analytic method and design tool adapted for preliminary design of permanent magnet axial flux machines, we begin by a two-dimensional study on a cylindrical section of the motor boring or average diameter illustrated by the figure 6.

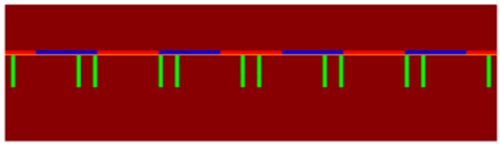


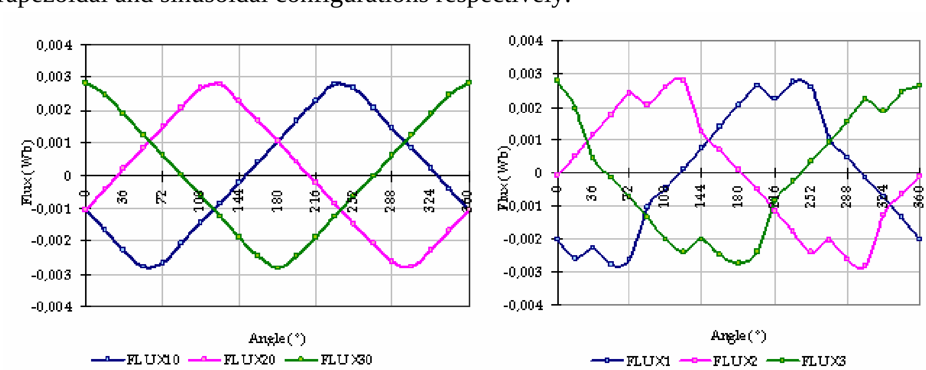
Figure 6: Two-dimensional representation in cylindrical cut

<u>Axial/radial transformation</u>

The study on the axial flux motor can be replaced by its equivalent with radial flux. In facts, the transformation is carried out on an average contour of the engine with axial flux. To have the same back E.m.f., it is necessary that the average diameter of the axial structure is equal to the average diameter of the motor with radial flux $D = (\frac{D_{ext} + D_{int}}{2})$, and the length of the radial motor L_m is equal to $\left(\frac{D_{ext} - D_{int}}{2}\right)$ [9].

4.2. Simulation results

The flux at load and at no load calculated by finite elements is illustrated by figures 7.a and 7.b for trapezoidal and sinusoidal configurations respectively.

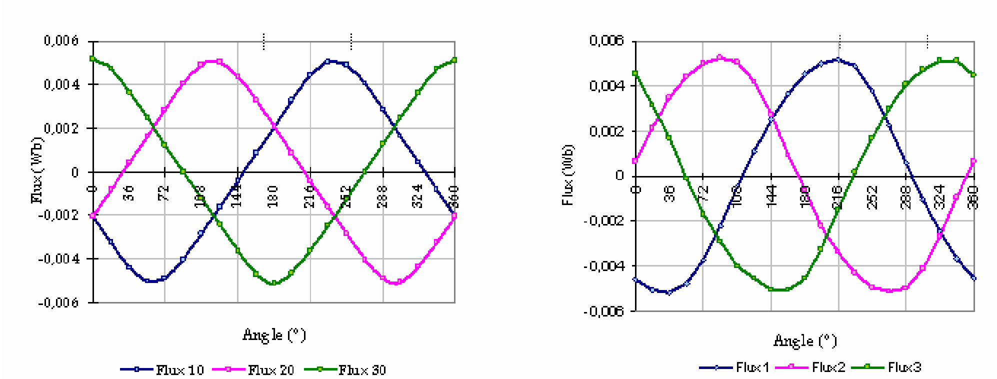


Flux at no load

Flux at load

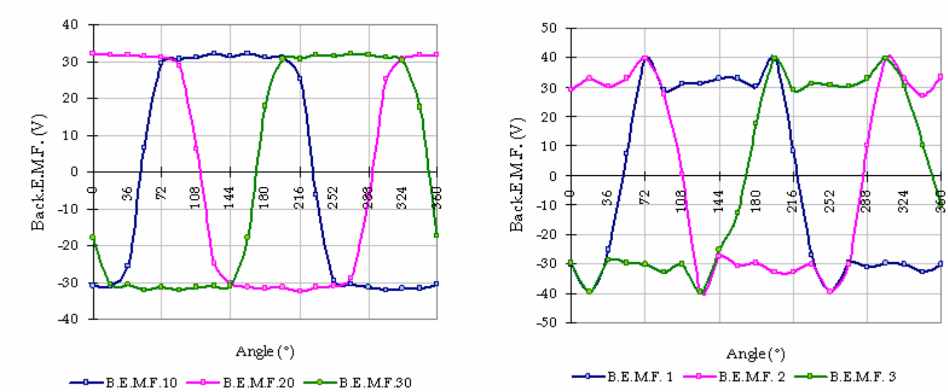
Figure 7.a: Three phase flux (Trapezoidal configuration)

Flux reaches the maximum value calculated by the analytical method which validates this approach. Flux is perfectly linear, which leads to obtaining perfectly trapezoidal back E.m.f. (figure 8.a.) for the trapezoidal configuration and sinusoidal back E.m.f. (figure 8.b.) for the sinusoidal configuration. This motor property reduces considerably the torque undulations.



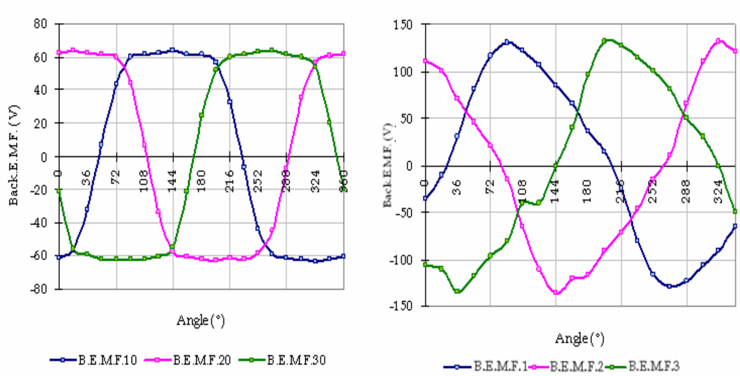
Flux at no load Flux at load

Figure 7.b: Three phase flux (sinusoidal configuration)



Back E.m.f. at no load Back E.m.f. at load

Figure 8.a: Three phase Emf (Trapezoidal configuration)



Back E.m.f. at no load Back E.m.f. at load

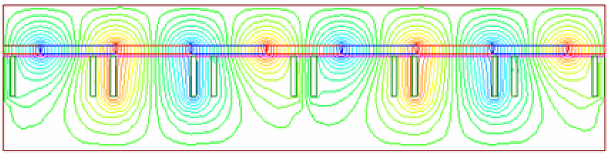
Figure 8.b: Three phase back E.m.f. (Sinusoidal configuration)

The electromagnetic torque is calculated by this equation:

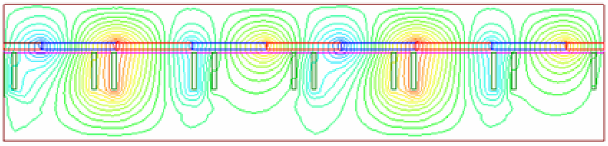
$$T_m(t) = \frac{1}{\Omega}\sum_{i=1}^{m} e_i(t) i_i(t) \quad (17)$$

where e_i is the Emf value of the i^{ème} phase. From the Back.E.M.F we can determine K_e .

Figures 9.a, 9.b, 10.a and 10.b illustrate respectively the field lines distribution at no load and at load for trapezoidal and sinusoidal configurations.

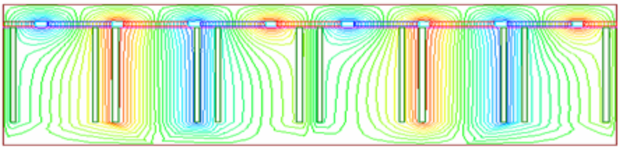


(a) Trapeze at no load

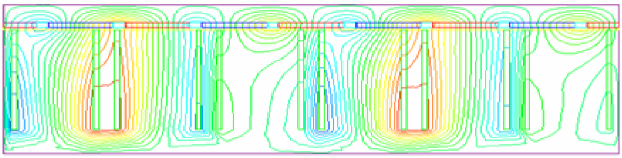


(b) Trapeze at load

Figure 9: Field lines distribution for trapezoidal configuration



(a) Sine at no load



(b) Sine at load

Figure10: Field lines distribution for Sine configuration

The field lines distribution shows that there is no magnet leakage. This property is obtained by geometrical optimization obtained by finite elements simulations [4].

The winding flux calculation of the first and the second phase by the finite elements method allows us the determination of phase inductance L_{ph} and the mutual inductance M .

By using the formulations (18) and (19) we obtain the values of L_{ph} and M :

$$L_{ph} = \frac{N_{sph}.\Phi_p}{I} \quad (18)$$

$$M = \frac{N_{sph} . \Phi_M}{I} \qquad (19)$$

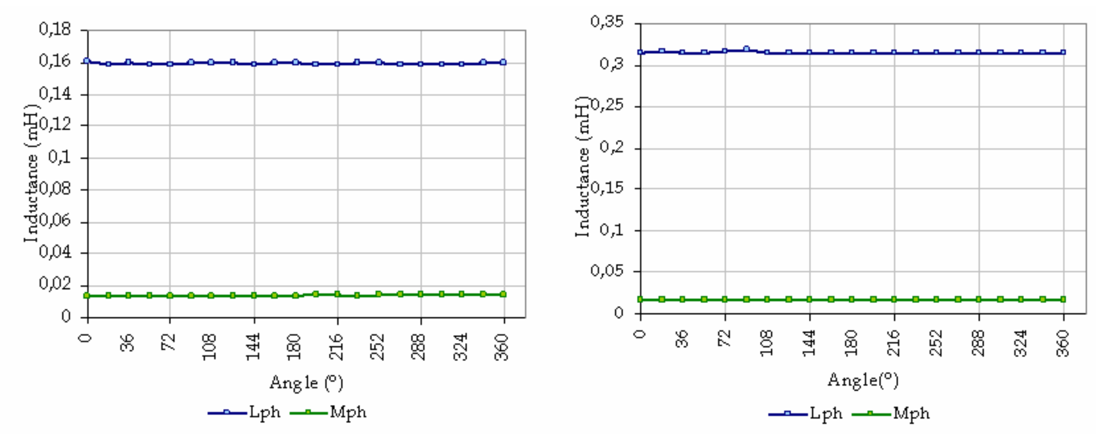
where:

I : current nominal one, L_{ph} : phase inductance of the motor,

M : mutual inductance by phase of the motor, Φ_p : magnetic flux of the fed whorl,

Φ_M : magnetic flux of the next not fed winding, N_{sph} : conductor number per whorl by phase,

The two figures 11.a and 11.b shows that the rotation of the rotor by an angle θ, has no influence on the inductances values for the trapezoidal and sinusoidal configurations. This result validates the analytical model.



(a) Trapezoidal configuration (b) Sinusoidal configuration

Figure 11: Invariance of inductances

Table I illustrate inductance values obtained by finite elements method (FEM):

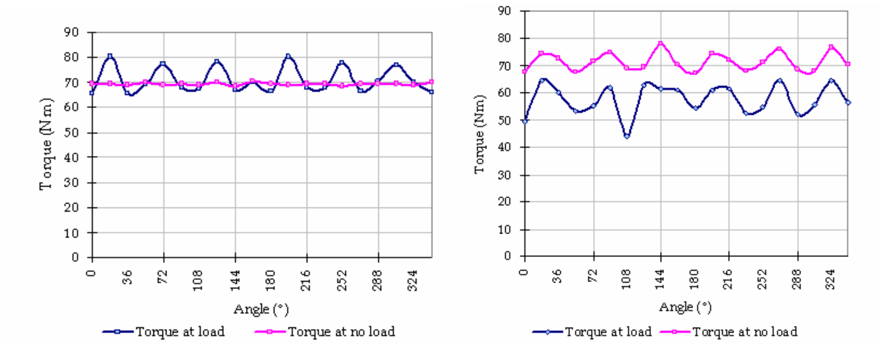
TABLE I: Values of inductances and the mutual inductances

	Trapezoidal configuration	Sinusoidal configuration
L_{ph-MEF} (mH)	0.158	0.314
$L_{ph-analytic}$ (mH)	0.147	0.274
M_{ph-MEF} (mH)	0.0138	0.0168
$M_{ph-analytic}$ (mH)	0.0137	0.0122

These results enable us to validate the values of analytically calculated inductances.

The backs E.M.F at no load and at load values enable us to determine the torque variations according to the swing angle.

The figures 12.a and 12.b, illustrate the torque variation of motor according to the swing angle at load and at no load for trapezoidal and sinusoidal configurations.



(a) Trapezoidal configuration (b) Sinusoidal configuration

Figure 12: Torque variation according to the swing angle

5. CONCLUSION

In this paper we presented a calculation method of the electric parameters for trapezoidal and sinusoidal configuration of a permanent magnets synchronous flux with axial flux by finite element method.

The results obtained for the trapezoidal and sinusoidal configuration validate the analytical model. Indeed in the first time we have determined and validated the analytical values of flux, electromotive force and torque calculated by the finite elements simulations, in the second time we have determined and validated the analytical values of inductance and mutual inductance calculated by the finite elements simulations.

This work developed will allow us to make possible control and optimization studies for these types of motors.

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